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THREE DECADES OF OUR GRADUATE RESEARCH AND EDUCATION IN COMPOUND SEMICONDUCTOR MATERIALS AND DEVICES

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Introduction

Research on compound semiconductors, beginning with Gallium Arsenide, started at Cornell in 1965. Emphasis has been on pure device-quality material, abrupt heterojunctions, and novel structures for microwave transistors and lasers. There have been 111 PhD and 41 MS degrees granted, and the effort of several senior staff members, and 81 visiting scientists were involved. Most are in U.S. industry and universities, with some in Europe and in the Far East. A substantial fraction of these participants have been involved in the industrial developments leading to the $15-20 Billion annual business in the compound semiconductor areas. This paper covers selected technical results from this early and extended Cornell program in this field.

Technical Results

Initial effort involved n-type GaAs operated in the transferred-electron (Gunn effect) mode of oscillation. Commercial bulk GaAs was given ohmic contacts and operated in the pulsed mode to limit over-heating. Peak power of ~ 6KW in L band [1], and > 1 KW at X band were achieved using thick samples operating in the limited space-charge accumulation (LSA) mode in special cavities. Liquid phase epitaxy was then developed, allowing controlled doping of thick layers of n-type GaAs. In the course of this effort, the first buffer layer was invented and named, to separate the substantial impurities and defects in the substrate from the active layer. The use of electric current through the layered stack of the GaAs source crystal, the melt, and the seed crystal, to control growth rate was made [2]. As part of the early liquid phase epitaxy, abrupt heterojunctions of lightly-doped n-type AlGaAs/GaAs were grown. At the urging of Prof. Herbert Kroemer, these were tested for I (V) across the heterojunction. They were the first strongly rectifying [3] such heterojunctions, experimentally proving his concept of carrier confinement at such interfaces. Next, pure InP [4] and $In_{.53}Ga_{.47}As$ [5] were grown by LPE to show their interesting properties. The current-controlled growth method was also used later, to control the growth of InP.

As part of the initial national submicron (nanofabrication) facility, established at Cornell in 1977, molecular beam epitaxy effort was started. Dr.Colin Wood joined Cornell to build up this MBE effort. The initial achievement was the lowering of electron trap densities, caused by arsenic anti-site defects, by three orders of magnitude, as determined by DLTS [6], [7]. Others later reversed this effect to cause higher trap densities for high resistivity and fast photo response. The first GaAs HEMT to outperform MESFET's was fabricated. The concept of atomic-planar doping (later renamed δ-doping) was initiated. Such atomic-layer doping of HEMT's, with a spacer layer between the doping plane and the 2DEG, was then initiated [8]. Using a 90 Å GaAs quantum well channel, between AlGaAs barriers, the first quantum well HEMT was made, limiting short-channel effects. Former students conceived of the use of a pseudomorphic quantum well on GaAs for improving these HEMT's. The first $Al_{.48}In_{.52}As$ barrier, for $Ga_{.47}In_{.53}As$ channels, both lattice-matched to InP substrates, was then conceived and grown [9]. This generic structure is now widely used in microwave transistors and in lasers for fiber-optical communication.

In order to achieve high performance transistors at high frequencies, the mushroom-cross-section gate was initiated, using tri-level resist in electron-beam lithography [10]. This method of making short gates, with low resistance along the gate, replaced the initial T-gate studied jointly with Hughes Research Laboratory, and formed with two layered metals, with a selective undercut etch of the bottom metal. It also involved self-aligned, ion-implanted ohmic contacts [11]. The latter T-gate transistor had established a record switching time of 15 PS. The former established record of 150 GHz = f_t, and 250 GHz f_{max}, for a .15 µm footprint gate on a GaAs HEMT.

The concept of ballistic electrons in compound semiconductors was initiated and named, with .25 eV electrons predicted to travel .18 µm at room temperature in GaAs , and 10's of microns at low temperature, when phonons are absent [12]. There have been several fundamental physical measurements, as well as novel quantum electron devices, that depend on these ballistic electrons. Direct measurements of this effect was made by Dr. M. Heiblum at IBM Research Laboratory, using a heterojunction potential step to launch the electrons [13]. Another of our innovative structures, the atomic-planar-doped barrier, also has interesting I(V) characteristics and can also be used to launch ballistic electrons. A ballistic injection HBT was also conceived [14].

Organo metallic vapor phase epitaxy OMVPE was also developed, initially for phosphide-related layers on GaAs substrates [15]. The initial AlGaInP red laser was fabricated. This laser is in wide use today. The InGaP/InGaAs/GaAs HEMT was then also studied, to show that it had higher current density and much less $1/f$ noise. The InGaP has a wide bandgap, and has no deep donors from the DX centers that occur in $Al_xGa_{1-x}As$ when (X) > (.22).

The initial pseudomorphic InGaAs quantum well laser was then grown and tested [16]. It had $In_{.37}Ga_{.63}As$ in the ~ 40 Å quantum well, yielding .99 μm wave length. This device was further developed elsewhere to provide .98 μm wave length pump light for Erbium-doped fiber amplifiers. The pseudomorphic quantum well laser had low threshold current density, because the light hole states in the valence band were raised up to the band edge by the strain. These states have a lower density due to the lighter hole effective mass, so lower current density was required to fill them. By going to 3 or 4 pseudomorphic quantum wells, it was possible to achieve direct modulation at higher frequencies with short laser cavities. A new state-of-the-art of 28 GHz for the 3db bandwidth of modulation was achieved at Cornell [17]. Later, a former student working with others at the Fraunhofer Applied Physics Laboratory in Freiburg, Germany, achieved a world record: 40 GHz bandwidth by the same technique.

For more than six years lately, Gallium Nitride and related alloys and compounds have been the emphasis. Both OMVPE [18] and MBE have been used to grow GaN and AlGaN/GaN and lately InN has been grown on sapphire as a substrate. AlGaN/GaN has also been grown on SiC for improved heat removal. Monte Carlo calculations were done to obtain the dependence of electron velocity on electric field. For GaN [19] it showed a peak electron velocity of ~ 2.8 $\times 10^7$cm/s at room temperature at 150,000 V/cm, and reduced velocity at higher electric field. For non-uniform electric fields, an average transit velocity of 2.0 – 2.5 x 10^7 cm/s was predicted, higher than obtained for most other compound semiconductors. In HEMT experiments to date, no more than 1.3 x 10^7 cm/s has been gotten. One unexpected experimental result was that for lower electron concentration, the electron mobility dropped, unlike the situation in other compound semiconductors. Because foreign substrates are not lattice-matched to the GaN epitaxial material, dislocations thread up through the latter. The dislocation density is ~ 5 x 10^8/cm^2 on SiC, and ~ 2 x 10^9/cm^2 on sapphire. A model was developed, with the dislocation representing a line of acceptors [20] with a band centered at ~ 2.15 eV below the conduction band. The electrons from the n-type background material are depleted around the dislocation, causing a potential rise. These potential rises scatter the electrons, lowering their mobility. This becomes dominant at lower (<10^{17}/cm^3) donor densities, where virtually all electrons are trapped at the dislocations, yielding > 1 x 10^8 Ω -cm resistivity in the undoped GaN.

There is a dominant electrical polarization in the nitrides, yielding a net positive bound electrical charge at the heterojunction of AlGaN/GaN when it is grown along the c-axis, of this Wurtzite crystal, on the Ga-face [21]. A one-year visit to Cornell, by Dr. Oliver Ambacher, on an Alexander von Humboldt Fellowship, transferred this technology. Undoped, polarization-induced 2DEG in these $Al_xGa_{1-x}N$/GaN HEMT structures were then developed, with .30 < x < .35. These yielded 1 – 1.3 x 10^{13}/cm^2 electron sheet density, with up to 1,700 cm^2/V-s electron mobility, using the OMVPE reactor developed by Prof. J. Richard Shealy. This reactor used a single flow, single pressure, single temperature method, unlike the much more complex method developed earlier in Japan. Optimized ohmic contacts, usually .3 - .5 Ω-mm, were developed using Ti/Al/Ti/Au annealed at 800°C for .5 – 1.0 minute. A substantial slump in drain current, power, and efficiency occurred when high drain bias was applied. This slump was eliminated by our invention of the PECVD Si_3N_4 passivation of the surface, which stabilized the charge in the surface states of exposed AlGaN. The state-of-the-art of power density was then established in 10 GHz class B operation of these polarization-induced AlGaN/GaN HEMT's [23]. It was 11-12 W/mm CW for .3 μm gates, and 100 μm wide channels biased to 45 V_{ds}, at 31%. power-added efficiency. It was 10 W CW for 10 channels, 150 μm wide, with 50 μm pitch, at 30 V_{ds}, at 40% power-added efficiency. These results are approximately an order of magnitude higher than GaAs HEMT's can deliver at the same frequency.

MBE growth of nitrides with Dr. William J. Schaff has recently come up with two important discoveries. One is that the MBE InN has ~ .85 eV bandgap at 300°K, not the value of 1.89 eV in the literature for many years. It has over 2,000 cm^2/V-s mobility at 300 °K, even with $10^{10}/cm^2$ dislocations and ~ 4 x $10^{17}/cm^3$ electron density. This mobility does not drop with reduced electron density, as is the case of GaN, but rises monotonically. Another is that MBE $Al_xGa_{1-x}N$, with X up to .80 μm(?), can yield $10^{20}/cm^3$ electrons when doped with Silicon. This latter result will allow improved performance of U.V. sources down to .28 μm wavelength. Together with the former result, InGaAlN can now be used over a very wide range of optical devices, from IR to U.V. wavelength.

Summary

In the 37 years of activity in this group's research on compound semiconductor materials and devices, much has been discovered, and many students have been educated. The materials include GaAs, AlGaAs, InGaAs, InAlAs, InGaP, GaN, AlGaN, and InN. The devices have included microwave MESFET's, HEMT's, and HBT's, as well as semiconductor lasers for high speed modulation. The students and results have been hired and transferred to industry, where they have made strong contributions to devices for radar and communication.

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